# Quantifying Geoacoustic Uncertainty and Seabed Variability for Propagation Uncertainty

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## LONG-TERM GOALS

Propagation and reverberation of acoustic fields in shallow waters depend strongly on the spatial variability of seabed geoacoustic parameters, and lack of knowledge of seabed variability is often a limiting factor in acoustic modeling applications. However, direct sampling (e.g., coring) of vertical and lateral variability is expensive and laborious, and matched-field and other long-range inversion methods fail to provide sufficient resolution. The long-term goal of this work is to use a Bayesian inversion approach in combination with seabed reflectivity data to investigate and quantify spatial variability of seabed sediments in two and three dimensions. For proper quantitative examination of spatial variability, it is important to differentiate between parameter estimate uncertainty, model parameterization effects, and actual spatial variability.

This project is based on work that was developed during Dettmer's PhD and postdoctoral research. To date, the project has developed an approach to quantify spatial variability of seabed sediments along a track (Dettmer et al. (2009a), Dettmer et al. (2009b)) and more recently developed advanced and general *trans-dimensional* inversion techniques (Dettmer et al. (2010)) that provide more realistic estimates of environmental parameter uncertainties than has previously been possible in the acoustic community. Further development of this methodology is an ongoing effort that will lead to rigorous two-dimensional (2D) and three-dimensional (3D) geoacoustic uncertainty estimation.

## OBJECTIVES

The objective of this research is to develop a new methodology to quantify 2D geoacoustic parameters

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and uncertainties to permit prediction of sonar performance uncertainties, as a step towards full 3D uncertainty estimation and verification. One-dimensional inversion results of wide-angle reflection data will be extended to 2D through sequential Bayesian inversion approaches and by interpolating geoacoustic parameters and uncertainties between reflection sites, guided by connecting data, when available (e.g., high-resolution seismic, towed-array acoustic data, AUV data), and prior information from geologic interpretations. Results will be verified by comparing transmission loss (TL) uncertainty predictions with measured TL. The methodology will be developed using a variety of existing data.

## APPROACH

To predict sonar performance uncertainties, 2D geoacoustic uncertainty models are needed along the track of interest. This project originally intended to develop such uncertainty models for the QPE experiment, where a $\sim$50 km x 50 km area off northeast Taiwan was chosen, including part of the Chilung shelf, the East China Sea shelf and upper slope. Unfortunately, weather and equipment problems prevented data acquisition. Thereafter, the focus shifted to spatially densely sampled wide-angle reflection data from the Malta Plateau in the Mediterranean Sea. These data provide a basis for developing and demonstrating the ability to recover rigorous high-resolution 2D geoacoustic uncertainty models.

Inferring geoacoustic parameters requires the assumption of a model describing the observed physical system including the physical theory, its appropriate parameterization, and a statistical representation for the data-error processes. In the past, Bayesian inference has been applied widely to geoacoustic inverse problems; however, model selection and comparison has seen only limited applications in acoustics. In addition, ambiguity and subjectiveness in the choice of model causes parameter uncertainties that have been ignored in geoacoustic inversion. The choice of model parametrization strongly influences parameter uncertainty estimates, with under-parametrized models generally under-estimating uncertainties while over-parametrized models over-fit the data and over-estimate uncertainties (Dettmer et al. (2009a)). Additionally, since the model is an approximation of the actual environment, the ambiguities resulting from this approximation cause parameter uncertainties that should be accounted for by integrating over the range of applicable parametrizations. In addition, parameter estimates can appear biased if an inappropriate parametrization is chosen.

One approach to address these issues is to compute the Bayesian evidence, which measures the likelihood that the data occured given the model under consideration. Bayesian evidence is a powerful but computationally difficult concept and was used by Dettmer et al. (2011) in geoacoustic inversion to pick the most likely model parametrization. Bayesian evidence is particulalry useful when an investigator is interested in how different choices of physical theory are supported by a measured data set but can be computationally expensive when many possible environmental parametrizaitons (e.g., the number of sediment layers) need to be considered. To address the latter, a trans-dimensional formulation of the geoacoustic inverse problem has been developed, where the number of parameters (environmental, data-error model, etc.) is itself an unknown in the problem (Dettmer et al. (2010)). This results in a trans-dimensional posterior probability density (PPD) that intrinsically addresses model selection and accounts for parameter uncertainty due to the range of model parametrizations by integrating over possible parametrizations rather than picking a single model. Trans-dimensional inference was introduced by Green (1995) and has since been applied to several problems in geophysics.

To sample from trans-dimensional distributions, Green (1995) generalized the Metropolis-Hastings

(MH) algorithm to the reversible-jump Markov chain Monte Carlo (rjMCMC) sampler that allows the Markov chain to transition between dimensions of the state space (i.e., the model parameter space) while maintaining detailed balance of the chain to obtain unbiased estimates. The rjMCMC formulation is based on an extended acceptance rule similar to MH acceptance and can be applied to a wide range of problems and dimension transitions. The rjMCMC methodology in this work also applies a partition modeling approach and trans-dimensional jumps of the birth-death form that allow for a straightforward implementation and application to AUV data. The partition model is applied to the layering structure of the seabed sediment by describing the sediment as an interval over a certain depth with layer interface locations determined by the data. Partition models have been shown (Bodin and Sambridge (2009)) to give results similar to regularized inversions when ensemble inference is carried out on the posterior. However, common regularizations used in geophysical inverse problems put subjective constraints on the solution, such as requiring the smoothest environmental model. With such regularization terms the parameter-uncertainty estimates are difficult to interpret. The partition model together with a trans-dimensional approach results in a naturally parsimonious self-regularization that is driven by the data (Bodin and Sambridge (2009), Dettmer et al. (2010)). Results combine the ability to resolve sharp discontinuities as well as to approximate smooth transitions (such as gradients) of arbitrary shape as determined by the data. The integrated “map” of interfaces shows increased probability where the data support structure.

## WORK COMPLETED

In the second year of this project, work has focused on developing a fundamentally new approach to quantify environmental parameter uncertainty for geoacoustic inversion (Dettmer et al. 2010).

In addition, these new techniques have been applied to initially analyze data that was collected by Charles Holland on the Malta Plateau by using an AUV with a Chirp source and a 32 element towed array.

A 170 core high performance compute cluster has been purchased, installed, and is administrated by Dettmer and Dosso at the University of Victoria. The cluster is jointly funded by ONR and the Natural Sciences and Engineering Research Council (NSERC) of Canada. The research carried out for this project is largely run on this computer and several inversion algorithms have been developed to take full advantage of the massively parallel architecture.

## RESULTS

Results presented in this section focus on some of the research carried out this year to develop a new approach to quantify geoacoustic uncertainty. A complete account is presented in Dettmer et al. (2010).

Figure 1 shows profile marginal distributions for interface location, sound velocity, density and attenuation obtained by trans-dimensional inversion of reflectivity data collected by Holland on the Malta Plateau using a fixed hydrophone and a surface towed impulsive source. There are four dominant peaks for layer interfaces, indicating four significant reflectors. Other areas of increased probability exist that do not show strong reflectors in the profile marginals. These areas exhibit velocity and density gradients that are captured through the ensemble and regularizing qualities of the trans-dimensional partition model. Figure 2 shows a histogram of the number of layers (interfaces) considered in the inversion which indicates that 5 interfaces has the highest probability for these data. However,

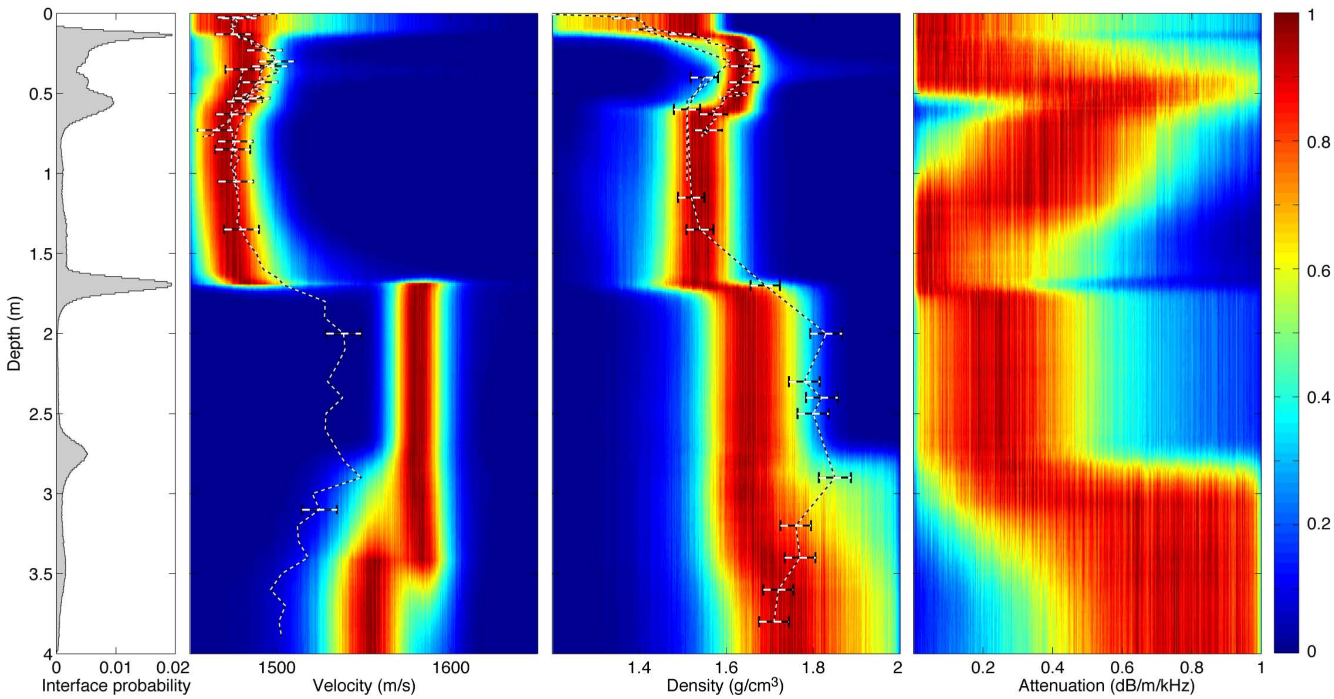


***Figure 1: Trans-dimensional geoacoustic inversion results for a site on the Malta Plateau. Cores taken at the site are given as dashed lines.***

significant probability exists for layering structure from 3–7 layers. This uncertainty in the number of interfaces supported by the data translates into an uncertainty for geoacoustic parameters and the position of interfaces that cannot be assessed in a fixed-dimensional approach. However, the trans-dimensional approach intrinsically accounts for this source of uncertainty, resulting in more realistic uncertainty estimates based on the information content of the data. In combination with a partitioning of the seabed, this results is a general approach that can be recognized as self-regularizing by the data. The agreement between core and inversion results is remarkable over the first 1.7 m. The inversion results match core values in both velocity and density and capture the shape of the profiles indicated by the cores. This is an indication of the data regularization intrinsic to the method, and suggests that the trans-dimensional approach can successfully approximate gradients by homogeneous layers where needed without over-fitting the data. To extract this information, it is crucial to rely on ensemble properties of the trans-dimensional PPD rather than point estimates such as the MAP model.

Figure 3 shows data collected by Charles Holland using an AUV towed array with 32 hydrophones. Holland carried out the experiment on the Malta Plateau in the Mediterranean Sea and developed processing techniques to extract reflection coefficients as a function of angle and frequency. This particular data set was measured for an AUV altitude of $\sim$12 m above the seafloor and processing involved averaging reflection-coefficient data of 10 adjacent pings (distance between pings $\sim$2 m) to reduce noise. Hence, the seafloor footprint of these AUV data (the area of spatial averaging) is $<$20 m. Figure 3 also shows the fit of inversion predictions to the data in terms of highest-probability density credibility intervals and a random subset of the PPD. To carry out the inversion, Holland and Dettmer developed a reflection coefficient forward model that accounts for spherical-wave effects and is efficient enough to be used in a trans-dimensional inversion, given parallel processing computing.

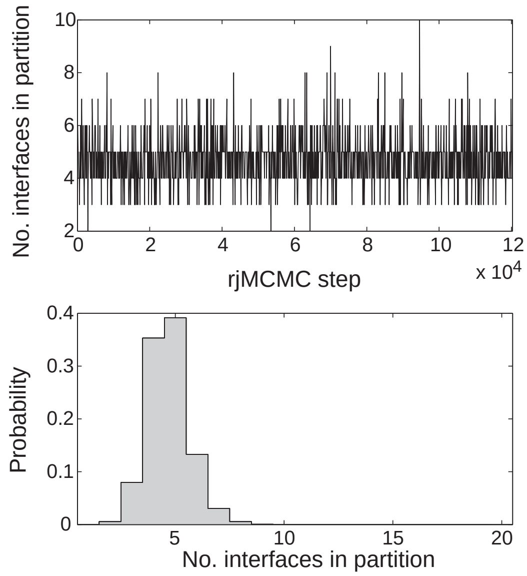


***Figure 2: Number of interfaces in the partition model.***

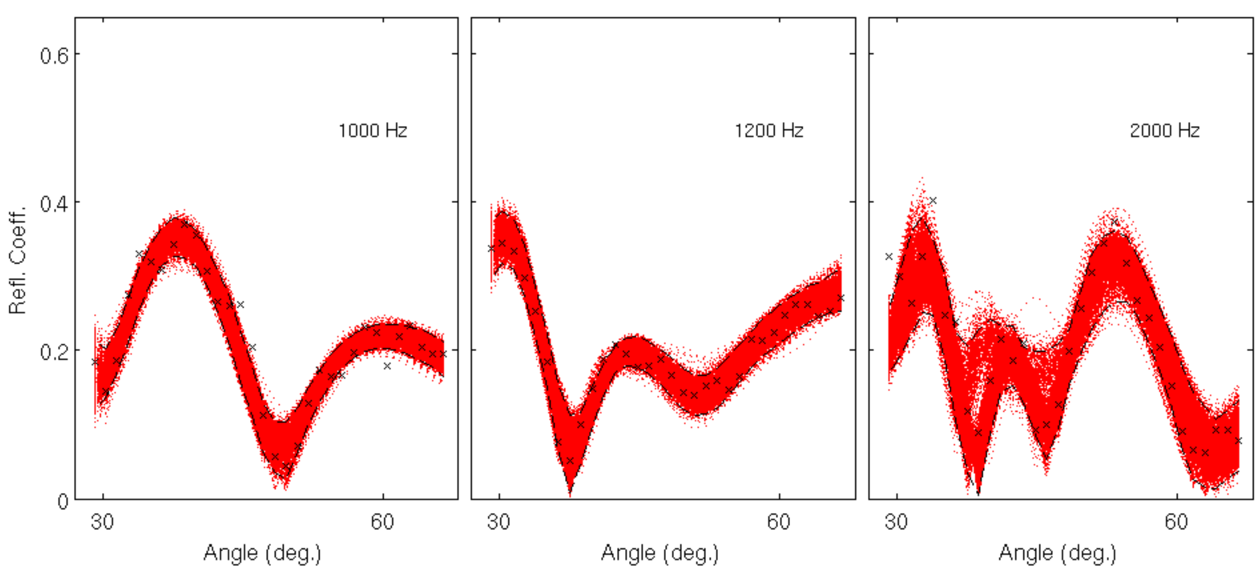


***Figure 3: AUV data measured on the Malta Plateau (crosses), PPD ensemble fit for 2000 randomly selected models (red), and 95% highest probability density credibility intervals (dashed).***

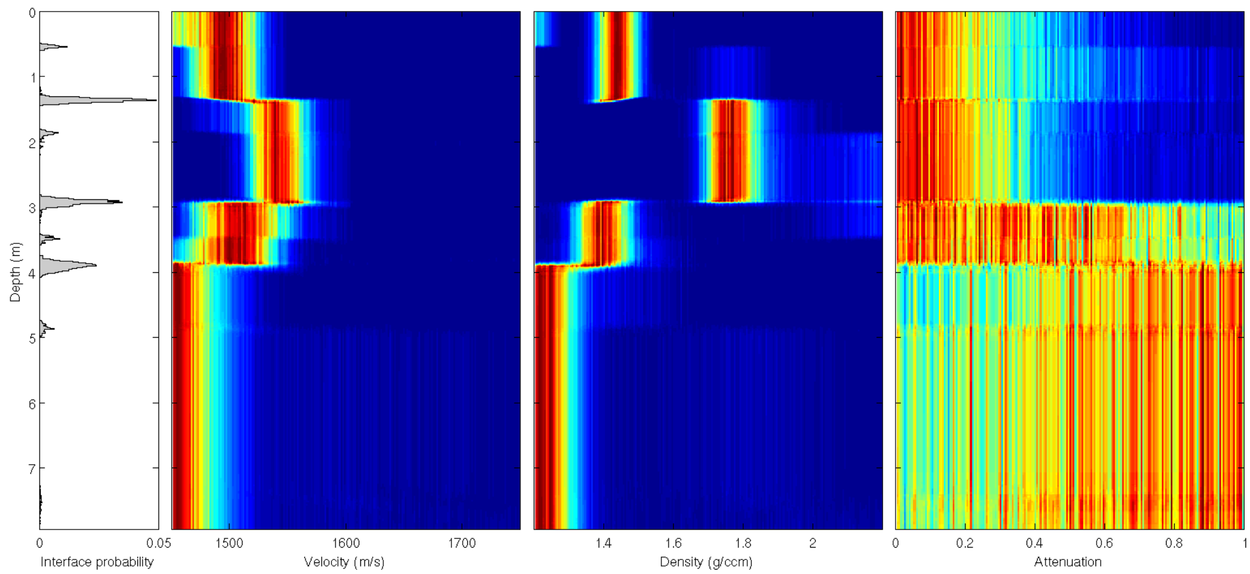


***Figure 4: Trans-dimensional inversion results for AUV data measured on the Malta Plateau.***

Figure 4 shows profile marginal distributions for the AUV data. Note that the angular coverage of the reflection coefficient measurement is small (28–66°, Fig. 3) but meaningful seabed structure is recovered in both sound velocity and density.

## IMPACT/APPLICATIONS

The ability to obtain seabed parameters remotely (i.e., without direct sampling) has important implications for science (e.g., providing data for understanding sediment processes), the Navy (improving databases for ASW and MCM), as well as many commercial applications (pipeline or cable laying). A particular strength of the present work is quantifying the uncertainties of the seabed parameters. Two-dimensional geoacoustic uncertainty models will impact the reliability and quality of transmission loss prediction.

## RELATED PROJECTS

Broadband Clutter JRP project (NURC, ARL-PSU, DRDC-A, NRL)
ONR QPE Uncertainty Program
Dossos NSERC Discovery Grant "Geoacoustic Inversion" (2009-2014) at the University of Victoria

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